Vibro-acoustic characteristics of TorHex honeycomb sandwich panels

Marianna Vivolo
K.U.Leuven, Department of Mechanical Engineering, division PMA
Celestijnenlaan 300B, B-3001 Leuven, Belgium
Marianna.Vivolo@mech.kuleuven.be

Bert Pluymers
K.U.Leuven, Department of Mechanical Engineering, division PMA
Celestijnenlaan 300B, B-3001 Leuven, Belgium
Bert.Pluymers@mech.kuleuven.be

Dirk Vandepitte
K.U.Leuven, Department of Mechanical Engineering, division PMA
Celestijnenlaan 300B, B-3001 Leuven, Belgium
Dirk.Vandepitte@mech.kuleuven.be

Wim Desmet
K.U.Leuven, Department of Mechanical Engineering, division PMA
Celestijnenlaan 300B, B-3001 Leuven, Belgium
Wim.Desmet@mech.kuleuven.be

Abstract

Studies on the interior acoustics of vehicles have lately strongly intensified. For cars, trains, airplanes and helicopters customers require a higher comfort level and also legislation tightens. To satisfy these new requirements, in the design phase new goals are set towards NVH (Noise Vibration and Harshness). It has become crucial to characterize structural components from a vibro-acoustic power point of view and to identify the main paths of noise and vibration transfer and of the sources involved.

This paper is focused on the evaluation of vibro-acoustic characteristics of sandwich panels with a TorHex core and homogenous material skin layers. Keeping the same systems' mass and surface area for all the examined cases, the stiffening effect of the TorHex core on the vibro-acoustic performance is investigated. The forced response, radiated power and radiation efficiency are numerically evaluated in a frequency range up to 4KHz and a comparison with homogenous panels is made. The numerical analyses consist of indirect boundary element analyses performed on the basis of structural modal based forced analyses. The resultant radiated acoustic powers are correlated to physical panel properties, such as stiffness and radiation efficiency. The sandwich panels show a quite good acoustic performance all over the frequency range of analysis. The associated radiated acoustic power levels are, particularly in the low frequency range, significantly lower than those of the corresponding homogenous plates. An optimization of the TorHex core design could allow to get valid alternative structures, suitable from both the structural and the acoustical point of view. Further work will focus in this direction.

Introduction

The use of lightweight materials is widely spread all over different application fields in the last decade. In the aerospace industry in particular, the weight savings combined with improved structural efficiency are directly translated into an increased payload, reduced operating costs and increased performances. However, although they yield a beneficial weight reduction, most often lightweight structures have a negative effect on the NVH behaviour. Sandwich structures in particular have many different applications and a lot of studies have already been performed in order to enhance their vibro-acoustic behaviour (Spilios E. Makris, 1986; O.Elbeyli, 2001; H. Denli, 2007; H. Denli, 2008). Sandwich structures consist of two faces (skin layers) separated by a lightweight core. One of the unique features of such structures is that by adjusting the material and geometric parameters of different layers in the structure, various sandwich constructions can be optimally designed, with regard to stiffness, mass, functionality, …, for special applications (P. Peters, 2006).

The research in this paper focuses on the analysis of sandwich structures with a TorHex core. A sample of such a sandwich material (faces of polypropylene reinforced with natural fibres) is shown in Figure 1. A TorHex core is a paper honeycomb core produced with an automated, in-line production process (J.Pflug, 2006). Intensive research on the mechanical properties of such sandwich structures has been already performed (J.Pflug, 2000; J.Pflug, 2002). This paper presents a study on the vibro-acoustic properties of TorHex panels. The radiation efficiencies, radiated acoustic powers and forced response amplitudes of three sandwich panels and two homogenous panels, with the same mass and surface area, have been numerically evaluated and compared, in a frequency range up to 4KHz. Structural damping has been discarded. The main goal of the present work is to identify the stiffening effect on the vibro-acoustic behaviour due to the core presence. Further investigations are planned to optimize both the structural and the acoustic performances of such a structure in specific frequency bands.

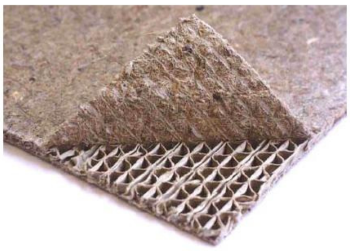


Figure 1 Sample of a TorHex sandwich panel with faces of PP/natural fibres

1. Coupled vibro-acoustic models

Five different systems have been numerically modelled. The Finite Element Method (FEM) is used to evaluate the structural in-vacuo modal behaviour of three sandwich panels (TorHex core) and two homogenous plates, calculating the natural modes up to 8KHz, while a fully coupled indirect boundary element method (I-BEM) is used to predict the vibro-acoustic behaviour up to 4KHz, for a known excitation case. The first three structures are equipped with the same core and all five panels have the same surface size and global mass. They have different thicknesses (the skin layer thickness for the sandwich ones and the plate thickness for the homogenous panels). Each individual sandwich panel has the same thickness for both the top and the bottom skin layer. Three different homogenous skin materials have been chosen: polypropylene reinforced with natural fibres (PP); aluminium and steel. The PP material consists of an isotropic polypropylene matrix in which natural fibres have been randomly distributed, thus, exhibiting mechanical properties which can be approximated as isotropic. For the homogenous cases an aluminum and a steel panel have been modelled. All of them are considered to be free-free panels, of dimensions 420x594mm (A2 standard size), with a weight of 1.64Kg. Structural damping has been discarded in the numerical modelling. Table 1 summarizes the panel information. The panels are excited by a normal point-force of 100N amplitude over a frequency range up to 4KHz. The software MD Nastran R3b has been used to carry out the modal analyses, while LMS-VirtualLab Rev8b is used for the coupled vibro-acoustic analyses.

Panel	Thickness	Mass [Kg]	Width	Length	Young's Modulus	Density
TorHex core	3.9mm	0.076	420mm	594mm	E_{MD} = 5GPa (see Fig.2)	636 Kg/m^3
PP skin sandwich	6.96mm	1.64	420mm	594mm	2 GPa	451 Kg/m^3
Al. skin sandwich	1.16mm	1.64	420mm	594mm	70 GPa	2700 Kg/m^3
St. skin sandwich	0.4mm	1.64	420mm	594mm	210 GPa	7850 Kg/m^3
Aluminium plate	2.43mm	1.64	420mm	594mm	70 GPa	2700 Kg/m^3
Steel plate	0.84mm	1.64	420mm	594mm	210 GPa	7850 Kg/m^3

Table 1 Geometric characteristics of the examined structures

The sandwich panels have been modelled starting from the single cell description. It is schematically shown in Figure 2 (left side), derived from the real structure, showed in Figure 2 (right side). The structural meshing process has been developed in order to evaluate modes up to 8KHz. Figure 3 shows the structural and the acoustic mesh used in the simulations, while Table 2 sums up some of the mesh details.

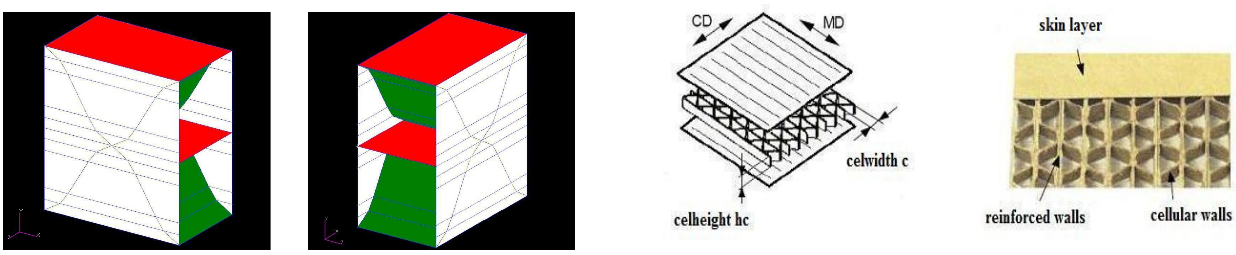


Figure 2 On the left: unity cell of the structural FEM. On the right: TorHex sample details

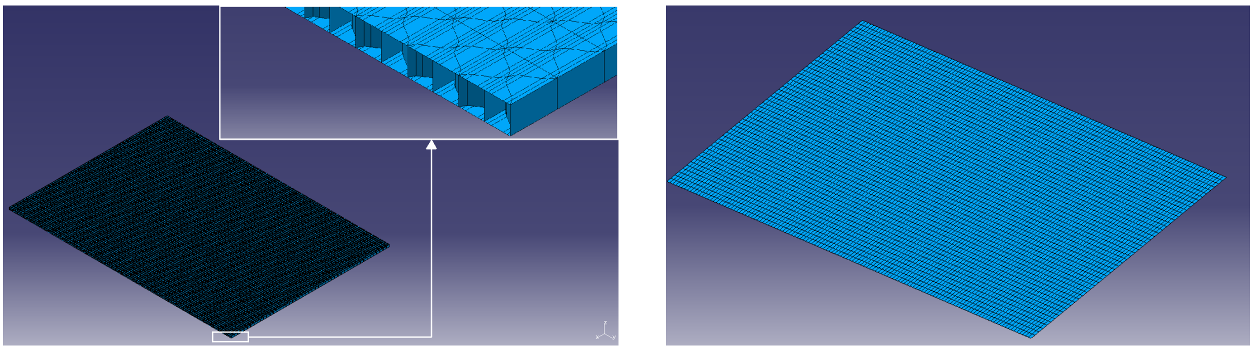


Figure 3 On the left: structural mesh (FE mode). On the right: acoustic mesh (BEM)

Mesh	number of nodes	number of elements
Structural	168.058	262.395
Acoustic	6.350	6.174

Table 2 Structural and acoustic mesh details

2. Numerical analysis results

2.1 Core stiffening effects

Keeping the same mass and surface size for all the panels, looking at their modal analysis results and at the structural responses, the effects coming from the core presence can be easily highlighted. The natural frequencies increase, going from the homogenous to the sandwich panels, as showed in Figure 4 (left side) for modes up to 1KHz. As is well known, they are directly proportional to the stiffness and inversely proportional to the mass.

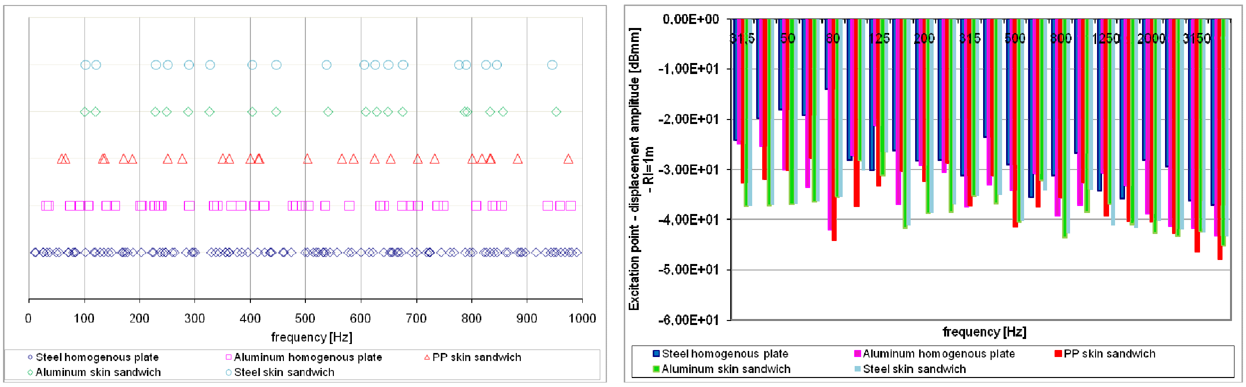


Figure 4 On the left: Natural frequency distribution up to 1KHz for the five models. On the right: Displacement amplitude at the excitation point, normal direction.

This shows that adding a core to a homogenous structure, creating in such a way a sandwich system, directly introduces the panel stiffness. Mostly the first frequencies (low frequency range) are influenced. In particular, the sandwich panel with PP skin seems to be the most flexible between the three lightweight structures considered here. Similar conclusions can be extracted from the structural forced response, looking at the displacement amplitude. Figure 4 (right side) shows the driving point response averaged in third octave frequency bands. The steel homogenous panel always shows the highest displacement levels, except in the third octave bands at 125Hz, 630Hz, 1250Hz and 1600Hz. In these bands the highest displacements belong to the aluminium homogenous plate. The high flexibility of the steel plate is due to its low thickness (0.84mm), to maintain the same mass as the other panels. Except for the very low frequencies (below 100Hz) the vibrating levels of these five plates becomes more and more similar going up in frequency, indicating again the dominant stiffness effect in the low frequency range.

2.2 Input power and radiated acoustic power

In the case of a mechanical system excited by a harmonic force, F, acting in a given excitation point, the mechanical power, W_{in} (time average), entering in to the system is directly linked to the real part of the product of the force times the complex conjugate (operator symbol *) of the velocity vector, v, in the excitation point

$$W_{in} = \frac{1}{2}\mathrm{Re}\left\{F \cdot v^{*}\right\}, \text{ with } v = j\omega x$$

In other words, it is directly linked to the displacement field in the excitation point, x, with ω being the angular velocity and j the imaginary unit.

In case any form of structural damping is discarded, the input power is equal to the radiated acoustic power, W_{rad}

$$W_{in} = W_{rad}$$

Figure 5 shows the radiated acoustic power evaluated for the aluminum homogenous plate and the aluminum skin sandwich panel (narrow frequency band).

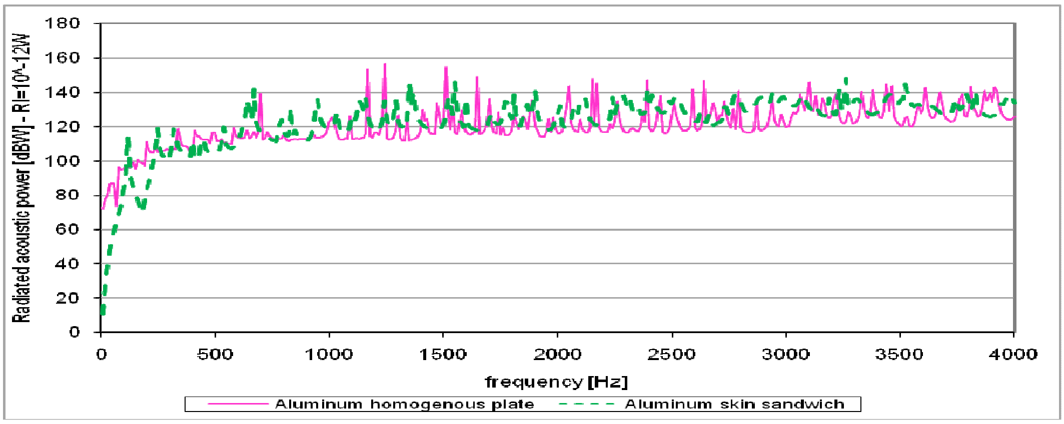


Figure 5 Radiated acoustic power for the aluminium homogenous plate and the aluminium skin sandwich panel

The radiated acoustic power has been evaluated for all the five systems introduced before, and their values (dBW), averaged in third octave bands, are showed in Figure 6.

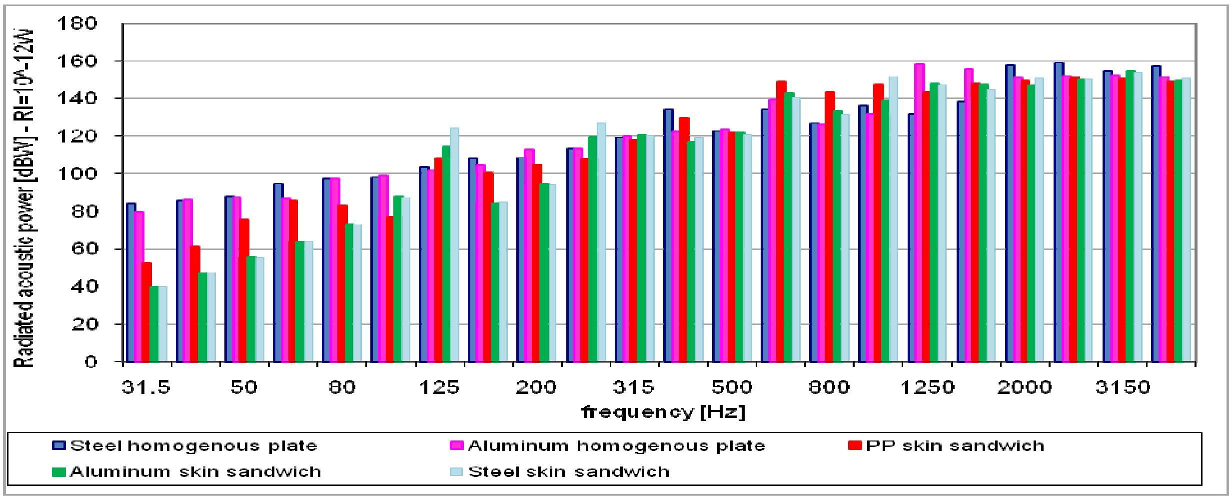


Figure 6 Radiated acoustic power from I-BEM simulations

In the lowest frequency bands the homogenous plates are radiating much more than the sandwich structures, but going up in frequency the difference between them tends to decrease and it happens that in some bands (i.e. 125Hz, 250Hz, 630Hz, 800Hz, 1000Hz,..) one or more of the lightweight panels radiates more.

2.3 Radiation efficiency

The radiation efficiency (σ) of a mechanical system is an important index in describing its vibro-acoustic behaviour. It represents the level of the acoustic power it is radiating compared to that of an equivalent infinitely rigid piston moving with the same energy level (mean quadratic velocity, v^2)

$$\sigma = \frac{W_{rad}}{W_{piston}}$$

For the case of a plate with surface S, radiating in a fluid (air) of density ρ_0 in which the acoustic waves propagate at the speed c_0, the radiation efficiency becomes

$$\sigma = \frac{W_{rad}}{S\rho_0 c_0 v^2}$$

Figure 7 shows σ for the five studied panels. When σ reaches the value 1, the coincidence frequency occurs. At this frequency the structural bending wavelength, λ_b, equals the acoustic propagation wavelength, λ_a, and it can be checked for thin homogenous plates, through well known analytic formula. For a panel of thickness h, made of a material with Young's modulus E, density ρ and Poisson's ratio ν, in which the bending waves propagate at the speed c_b, it comes from the following expressions

$$\lambda_b = \lambda_a \Rightarrow \frac{c_b}{f} = \frac{c_a}{f}, \text{with } c_b = \sqrt{2\pi f}\sqrt[4]{\frac{Eh^2}{12\rho(1-\nu^2)}} \text{ and } c_a = 340 m/s$$

The coincidence frequency is 4920Hz and 14KHz for the aluminum and steel studied plates, respectively.

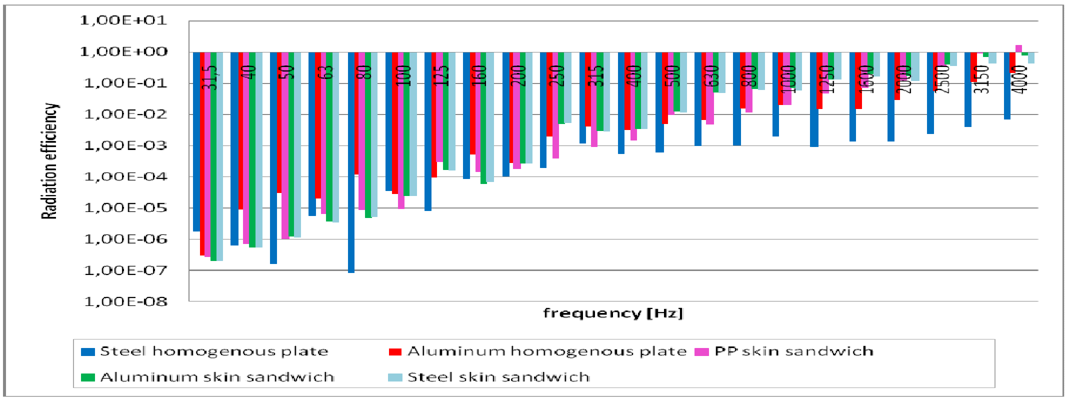
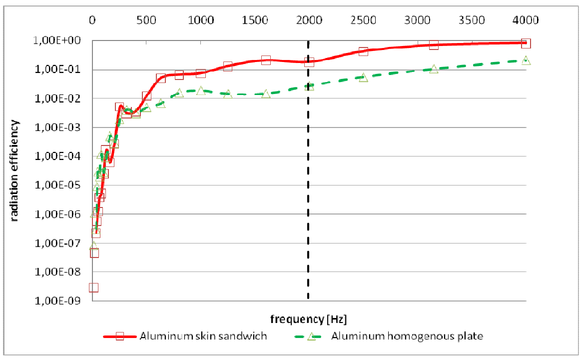


Figure 7   Radiation efficiency, third octave bands (log vertical scale)

It can be that a higher radiation efficiency corresponds to a higher radiated power level. This is true for example in the low frequency region, but when the frequency increases and the phenomena begin to be of smaller scale, the effects of the core geometry and its mechanical properties, become more and more important.

Considering in more detail the 2000Hz frequency band, comparing the aluminum homogenous plate and the sandwich panel with aluminum skin and keeping in mind they have the same mass and surface area, Figure 8 and 9 show that, even if the homogenous plate exhibits a better (lower) radiation efficiency, it is radiating more acoustic power.



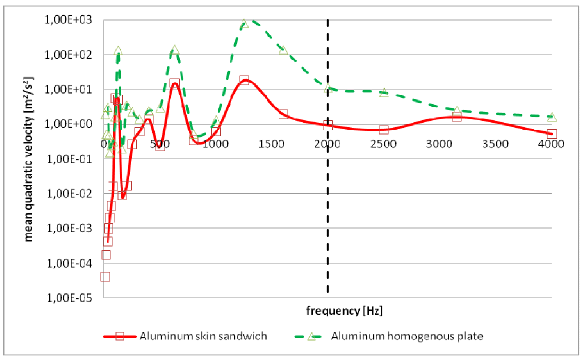


Figure 8 Radiation efficiency (left side) and mean energy level (right side): comparison homogenous aluminium plate VS aluminium skin sandwich panel

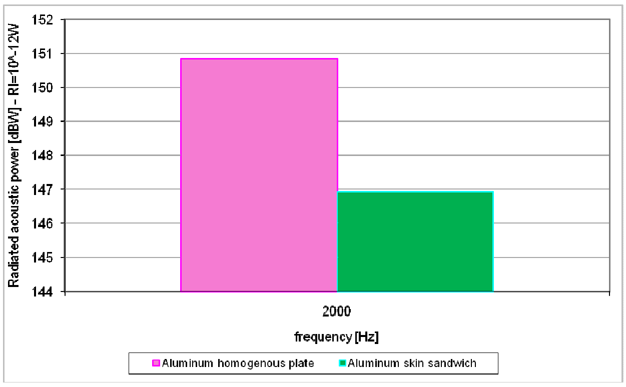


Figure 9 Aluminium homogenous plate and aluminium skin sandwich: radiated acoustic power

The mechanical behaviours of these two systems play here a fundamental rule. The radiated power can be seen as directly proportional to the radiation efficiency and the system energy (the mean quadratic velocity).

$$W_{rad} \propto \sigma \cdot v^2$$

Thus, having a look at the vibrating mean level at this frequency band (Figure 8 right side), it is found out that for the aluminum sandwich structure, this is much lower than for the homogenous system, and this difference is higher than the difference in terms of radiation efficiency (Figure 8 left side).

3. Conclusions

TorHex core sandwich panels have firstly been regarded for their mechanical characteristics and a fast and continuous production process has been patented at K.U.L. (Pflug, 2001). This paper looks at their vibro-acoustic performance and highlights their potential meaning as a valid alternative to the current homogenous material component in the automotive industries (Pflug, 2003). The effect of the stiff core plays an important rule and encourages further studies in order to optimize the core design itself and achieve desired vibro-acoustic behaviours in some specific frequency regions, with no modifications in mass and size. This paper shows how the radiation efficiency and the mechanical global behaviour combine together to bring about the radiated acoustic power. And illustrates that only knowing the radiation ability of the system is not enough in order to predict its acoustic behaviour. For the same reason, the lightweight structures can be optimally designed also to achieve good acoustic performance, keeping their mechanical attractive skills. Future works will aim to the core and skin layer design optimization, in order to achieve a desired vibro-acoustic behaviour of such structures in specific applications.

Acknowledgements

The authors kindly acknowledge the European Commission for their support of the Marie Curie EST project SIMVIA2 (http://www.simvia2.eu, contract nr. MEST-CT-2005-020263), from which Miss. Marianna Vivolo holds a Research Training grant. Also the Fund for Scientific Research - Flanders (F.W.O.), Belgium, is gratefully acknowledged for their research support.

4. References

1. Spilios E. Makris, Clive L. Dym and J. MacGregor Smith. (1986). 'Transmission Loss optimization in acoustic sandwich panels', College of engineering, University of Massachusetts, Amherst, Massachusetts
2. O.Elbeyli, P.Thamburaj and J.Q.Sun. (2001). 'Structural-Acoustic studies of Sandwich Structures: A Review', *The Shock and Vibration Digest, Vol.*33, *No.*5, pp.372
3. H. Denli, Author and J.Q. Sun. (2007). 'Structural-acoustic optimization of sandwich structures with cellular cores for minimum sound radiation', *J. Sound and Vib.* 301*,* pp. 93-105
4. H. Denli, Author and J.Q. Sun. (2008). 'Structural-acoustic optimization of sandwich cylindrical shells for minimum interior sound transmission', *J. Sound and Vib.* 316*,* pp. 32-49
5. Portia P. Peters, Dr. Shankar Rajaram and Dr. Steven Nutt (2006). 'Sound transmission loss of damped honeycomb sandwich panels', *INTER-NOISE,* Honolulu, USA
6. J.Pflug I.Verpoest and D.Vandepitte (2000). 'Folded honeycomb cardboard and core material for structural applications', *Proceedings of the 5th Sandwich Construction conference,* Zurich
7. J.Pflug and F.Xinyu (2002). 'Development of sandwich material with polypropylene/natural fibre skins and paper honeycomb core', *Proceedings of 10th European Conference on Composite Materials (ECCM-10),* Belgium, paper 331
8. J. Pflug, I. Verpoest (2001) 'Folded-sheet honeycomb structure (Faltwabe) ', *patent application PCT/EP96/03121, granted as European patent EP0839088 (Nov. 1999) and as American patent US6183836*
9. J. Pflug, B. Vangrimde, I. Verpoest (2003) 'Material efficiency and cost effectiveness of sandwich materials', *Sampe Conference*, Longbeach, USA